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The rational footsteps for the design of the mechanism of a vertical carousel-type storage device

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Abstract

The number of design parameters in a vertical carousel-type storage device is larger than the number of functional requirements, which makes it a redundant design. The usual design approach for this kind of mechanical systems is based on trial and error. The aim of this paper is to present a method that leads to the most appropriate sequence in the design of these machines. With this propose in mind, the design equation of the system was examined and subsequently rearranged, so that it reveals that its motion subsystem could be regarded as a decoupled design. This allowed establishing a set of rational footsteps that were used to design the aforesaid system, as described in the paper.

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1. Introduction

In the beginning of the process of designing a new machine, the designer is usually faced with some common situations, such as:

- The number of design parameters is too large;
- The number of design parameters is greater than the number of functional requirements;
- Several design parameters are interrelated;
- The range of values of some design parameters is unknown.

This corresponds to the description of a typical redundant design. Any good design solution complies with independence axiom [1], so that sometimes trial and error is used as to attain an appropriate set of design parameters. Given the large amount of design parameters, the generally applied strategy consists in fixing some design parameters, through system constraints, or through relationships between design parameters, in order to establish a sequence that allows defining the remainder design parameters, as to fulfil the complete set of functional requirements.

This procedure aims at obtaining a design equation with a squared design matrix, that is, an equation with FRs and DPs in equal number [1], as explained in section 2.

To illustrate the procedure, a vertical, carousel-type storage device is used as an example. This is done in sections 3 to 5. At last, conclusions are presented in section 6.

2. Dealing with redundant designs

The term redundant may be used with different meanings [2]. In what concerns to Axiomatic Design, according to Suh's theorem 3, "When there are more DPs than FRs, the design is a redundant design, which can be reduced to an uncoupled design or a decoupled design, or a coupled design." [3]. In

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addition, theorem R1 states, "All redundant designs with right-trapezoidal matrices are decoupled" [4]. Moreover, theorem R2 states, "Redundant designs with design matrices composed by contiguous diagonal blocks are uncoupled". In other words, a corollary to theorem R2 states, "Design matrices with one only nonzero element per column correspond to uncoupled designs" [4].

As one can see, Axiomatic Design provides the basic tools that are required to identify uncoupled and coupled redundant designs.

Taking into account theorem R1, Eq. 1 illustrates a 2-FR, 4-DP example of a redundant decoupled design.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & 0 \\ A_{21} & A_{22} & A_{23} & A_{24} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \tag{1}$$

Eq. 1 shows that one has to fix two DP's as to determine the other two. Let's suppose that we fix $DP_1$and DP_2. In this case, we have

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{13} & 0 \\ A_{23} & A_{24} \end{bmatrix} \begin{Bmatrix} DP_3 \\ DP_4 \end{Bmatrix}, \tag{2}$$

since DP_1 and DP_2 have been previously fixed. As we can see, Eq. 2 represents a decoupled deign, as we could expect since this equations derives from Eq. 1.

Sometimes, things are not so easy, as is the case where DP's are linked through system constraints. For example, let us suppose that DP_1 and DP_3 are linked through system constraint C_1 and that DP_2 and DP_4 are linked through system constraint C_2. In this case,

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & 0 \\ A_{21} & A_{22} & A_{23} & A_{24} \end{bmatrix} \begin{Bmatrix} C_1 DP_3 \\ C_2 DP_4 \\ DP_3 \\ DP_4 \end{Bmatrix} \tag{3}$$

and Eq. 3 can therefore be written as

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} + \dfrac{A_{12}}{C_1} + A_{13} & 0 \\ \dfrac{A_{21}}{C_1} + \dfrac{A_{22}}{C_2} + A_{23} & A_{24} \end{bmatrix} \begin{Bmatrix} DP_3 \\ DP_4 \end{Bmatrix}. \tag{4}$$

Again, Eq.4 shows the decoupled nature of the design.

In the example presented in the following sections, the system constraints are the ones that are typical in problems of mechanisms.

3. The vertical carousel storage device

The design of a vertical carousel storage device was considered as to satisfy the following customer needs:

- Number of objects to be stored;
- Length , width and height of the largest object to be stored;
- Weight heaviest object to be stored.
- Small footprint

Vertical carousel storage devices are based on the "Ferris wheel" concept. Objects are stored in rotating shelves, so that each shelf is presented to the user, who has not to move, whether storing or retrieving the objects. In this manner, the shelves move towards the user instead of the opposite.

The Ferris wheel is composed by two parallel wheels spinning on the same axle that is held by two masts. Seats or cabins are installed between the wheels and are held by bearings, so that they keep their orientation along the circular motion. Vertical carrousel storage units are a kind of modified Ferris wheels with a shape that is similar to chain bucket elevators, as to reduce their footprint. Fig. 1 shows a vertical carousel storage device, as provided by online manufacturer's catalogues [5, 6].

Fig. 1. Examples of vertical carousel storage units [5, 6]

A comparison between a conventional storage system with motionless shelves and a vertical carousel storage device is shown in Fig. 2 [7].

Fig. 2. Comparison between a motionless storage system and a vertical carousel storage unit [7]

As one can see, the main characteristics of the vertical carousel storage unit and of its support and displacement sub-system are listed below.

- Number and size of selves;
- Size of chains, sprockets and support bars for the shelves;
- Overall dimensions of the vertical carousel storage, such as length, width and height ;
- Power required to drive the machine.

The mechanical system for the translation of the shelves is the focus of this article.

4. The conceptual development based on Axiomatic Design

The considered FR’s are supposed to fulfil the customer needs, as well as some system constraints that emerge during the decomposition. These constraints result from the geometry and the kinematics of the combined mechanisms that are used to embody the carrousel. As to the input constraints, such as cost and safety, they are supposed to be fulfilled.

At the first hierarchic level, the functional requirement is

FR_1 – Storage with automated stowing,

to which corresponds the design parameter

DP_1 – Vertical carousel storage unit.

Eq. 5 shows the design equation for this hierarchic level

$$\left\{FR_1\right\}=\left[\times\right]\left\{DP_1\right\}, \qquad (5)$$

The second hierarchic level is composed by the following functional requirements and design parameters:

$FR_{1.1}$ – Hold stored objects;
$FR_{1.2}$ – Move objects for reception and delivery at the same location;

$DP_{1.1}$ – Set of shelves to store objects;
$DP_{1.2}$ – System for moving and supporting the shelves, based on a modified design of the Ferris wheel.

Eq. 6 shows the design equation at this level.

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \end{Bmatrix} = \begin{bmatrix} \times & \times \\ 0 & \times \end{bmatrix} \begin{Bmatrix} DP_{1.1} \\ DP_{1.2} \end{Bmatrix}, \qquad (6)$$

In the third hierarchic level, the functional requirements are

$FR_{1.2.1}$ – Move the shelves keeping them upright;
$FR_{1.2.2}$ – Drive the movement of the shelves;
$FR_{1.2.3}$ – Minimize the volume of the device;
$FR_{1.2.4}$ – Avoid collision between the shelves;
$FR_{1.2.5}$ – Synchronize the motion of both hinges of the shelf;
$FR_{1.2.6}$ – Support the whole device.

The corresponding design parameters are:

$DP_{1.2.1}$ – Shelf hinge;
$DP_{1.2.2}$ – Arm roller and position rails;
$DP_{1.2.3}$ – Chains and sprockets;
$DP_{1.2.4}$ – Rollers and guide rails;
$DP_{1.2.5}$ – Electrical motor gear;
$DP_{1.2.6}$ – Power transmission;
$DP_{1.2.7}$ – Multi-link system to offset the shelves;
$DP_{1.2.8}$ – Shaft connecting the drive sprockets;
$DP_{1.2.9}$ – Bearings of the shafts;
$DP_{1.2.10}$ – Metallic supporting structure.

The shelves are linked to the chains through a multi-link system ($DP_{1.2.7}$) in order to avoid collisions. The system is driven at the regions where the direction of the motion of the shelves is reversed, as to move away the shelves from the chains. Eq. 7 shows the design equation at the third level. This equation represents a redundant design as per theorem R1.

$$\begin{Bmatrix} FR_{1.2.1} \\ FR_{1.2.2} \\ FR_{1.2.3} \\ FR_{1.2.4} \\ FR_{1.2.5} \\ FR_{1.2.6} \end{Bmatrix} = \begin{bmatrix} \times & \times & \times & \times & \times & \times & 0 & \times & 0 & 0 \\ 0 & 0 & \times & 0 & \times & \times & 0 & \times & 0 & 0 \\ 0 & 0 & \times & \times & 0 & 0 & \times & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \times & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \times & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \times & \times \end{bmatrix} \begin{Bmatrix} DP_{1.2.1} \\ DP_{1.2.2} \\ DP_{1.2.3} \\ DP_{1.2.4} \\ DP_{1.2.5} \\ DP_{1.2.6} \\ DP_{1.2.7} \\ DP_{1.2.8} \\ DP_{1.2.9} \\ DP_{1.2.10} \end{Bmatrix} \qquad (7)$$

Fig. 3 shows the driving subsystem, in which the above-mentioned design parameters are identified.

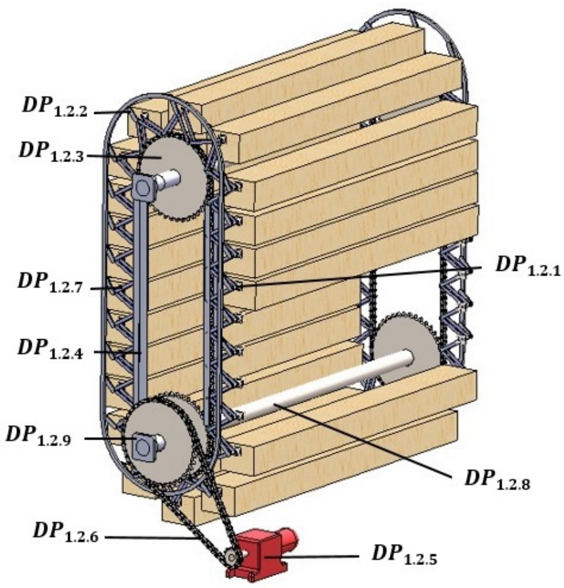

Fig. 3. The design parameters of a vertical carousel storage unit

Fig. 4, shows the result of the zigzag decomposition for the aforesaid three levels.

At the third level, the mismatch between the six functional requirements and the ten design parameters is easily observed. According to theorem 3 (Redundant Design), when there are more DPs than FRs, the design is a redundant design, which can be reduced to an uncoupled design or a decoupled design, or a coupled design [3].

Moreover, theorem 4 (Ideal Design) states that in an ideal design, the number of design parameters (DPs) is equal to the number of functional requirements (FRs) and FRs are always maintained independent from each other [3].

By analysing the various design parameters, one can identify the relationships between them, which represent the system constraints that result from the geometry and kinematic laws of the linked mechanisms. These interdependencies allow grouping several design parameters into single design parameters. Among others, the most important system constraints are:

- The size of shelves depends on the size of the largest object to be stored.
- The pitch of the shelves depends on the height of the tallest object to be stored.
- The number of shelves depends on the number of objects to be stored.
- The length of the chains must be such that ensures the uniform distribution of the shelves.
- For the same reason the pitch of the shelves must be a multiple of the chain's pitch.
- The length of the chain corresponding to the pitch of the shelves must have an even number of links, as to preclude the use of cranked-link joints.

Besides the geometric relationships, specific values for some design parameters were also established, as for example:

- The dimensions of chains, spacing bars, fastening systems of shelves, sprocket wheels and support bearings of the shafts, among others, are not yet known at the initial stage of the design. Thus, it is assumed that the space occupied by those components corresponds to 10% of the length of the largest object to be stored. Because those components are replicated in both sides of the shelves, then the length of the shaft linking the sprockets should be 20% larger than the length of the longest object to store.
- The hinges of the shelves must be located well above the position of the centre of mass of the loaded shelves, typically at 75% of the height of the load, for a matter of stability.
- To avoid collisions, a gap of 10% of the height of the loaded shelves should be adopted.
- For power calculation, it was assumed that the mass of each shelf is taken as 20% of the total mass to displace.
- It is also assumed that the maximum linear speed of the chains is 0.5 m/s.

The design parameter $DP_{1.2.1/2}$, which will be called "Shelf Positioner", results from joining the design parameter $DP_{1.2.1}$ (Shelf hinge) with the design parameter $DP_{1.2.2}$ (Arm roller and position rails).

The design parameter $DP_{1.2.3/4}$, which will be called "Support and Displacement Subsystem", results from clustering the design parameter $DP_{1.2.3}$ (Chains and sprockets) with the design parameter $DP_{1.2.4}$ (Rollers and guide rails).

The design parameter $DP_{1.2.5/6}$, which will be called "Driving System", results from the junction of the design parameter $DP_{1.2.5}$ (Electrical motor gear) with the design parameter $DP_{1.2.6}$ (Power transmission).

The design parameter $DP_{1.2.9/10}$, which will be called "Supporting System", results from joining the design parameter $DP_{1.2.9}$ (Bearings of the shafts) with the design parameter $DP_{1.2.10}$ (Metallic support structure).

The design parameter $DP_{1.2.7}$ (Multi-link system to move away the shelves) and the design parameter $DP_{1.2.8}$ (Shaft connecting the drive sprockets) remain isolated because they have no direct relationship with any other design parameter.

As one could see, grouping interrelated design parameters yields to a smaller number of design parameters, equalling the number of functional requirements.

$FR_{1.1}$ does not relate to the driving system and was not decomposed for a matter of simplicity.

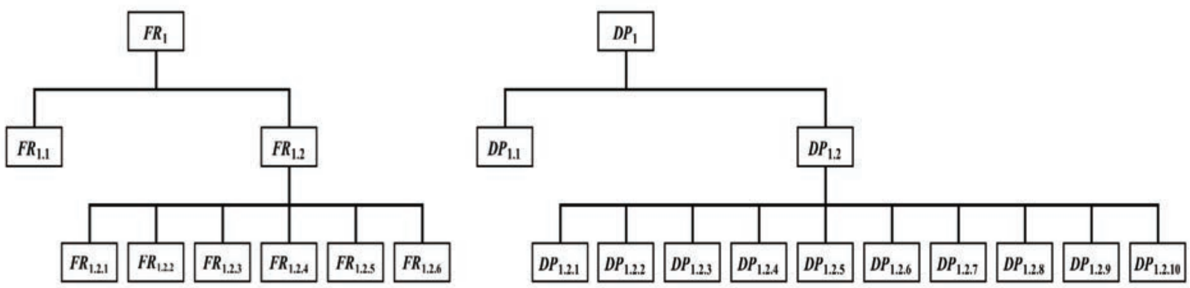

Fig. 4. The result of the zigzag decomposition regarding Eq. 5, 6 and 7

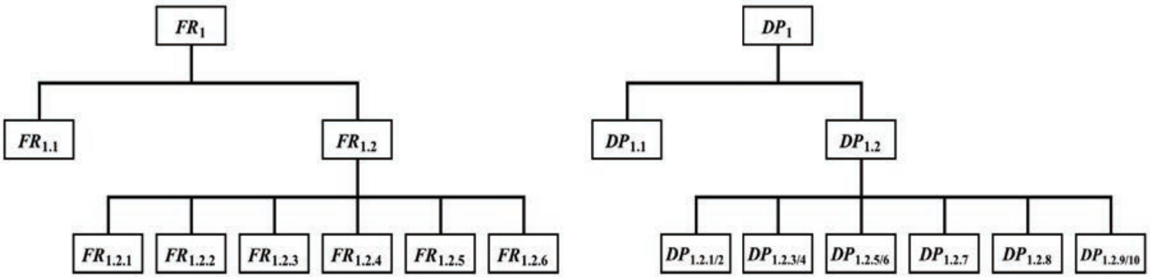

Fig. 5. The result of the zigzag decomposition regarding Eq. 5, 6 and 8

As a result, the new clustered design parameters were used to replace the ones that are shown in Eq. 3. This allows rewriting Eq. 7 as Eq. 8, so that the number of design parameters equals the number of functional requirements. Eq. 8 has been rearranged, by changing the order of $DP_{1.2.3/4}$ and $DP_{1.2.5/6}$, as to obtain a triangular matrix, thus stressing the decoupled nature of the design.

$$\begin{Bmatrix} FR_{1.2.1} \\ FR_{1.2.2} \\ FR_{1.2.3} \\ FR_{1.2.4} \\ FR_{1.2.5} \\ FR_{1.2.6} \end{Bmatrix} = \begin{bmatrix} \times & \times & \times & 0 & \times & 0 \\ 0 & \times & \times & 0 & \times & 0 \\ 0 & 0 & \times & \times & 0 & 0 \\ 0 & 0 & 0 & \times & 0 & 0 \\ 0 & 0 & 0 & 0 & \times & 0 \\ 0 & 0 & 0 & 0 & 0 & \times \end{bmatrix} \begin{Bmatrix} DP_{1.2.1/2} \\ DP_{1.2.5/6} \\ DP_{1.2.3/4} \\ DP_{1.2.7} \\ DP_{1.2.8} \\ DP_{1.2.9/10} \end{Bmatrix} \quad (8)$$

Fig. 5 depicts the functional and the physical trees that correspond to Eq. 8.

The design parameters were found according to a "top-down" approach that is based on the customer needs. The mathematical model that concerns to the geometry and the kinematics of the system was developed using a "bottom-up" approach that encompasses the following main procedure [8]:

- Analysis of functional requirements and of the selected design parameters, in order to ascertain the “goodness” of the proposed solution, as to ensure that it is not a coupled design.
- Consideration of the relationships between the design parameters based on the system constraints.
- Accomplishment of the equations that define the main characteristics of the design parameters.

5. Conclusions

The above-described procedure made it possible to develop a compact mathematical model with a squared design matrix that allowed defining the main dimensions of the vertical carousel storage unit and of its support and displacement subsystem that fulfil the needs of the customer.

The analysis of the functional requirements and of the matching design parameters of the vertical carousel storage unit allowed establishing the corresponding design equation. This equation, with a rectangular design matrix, shows that there are more design parameters than functional requirements. Moreover, the way the matrix is populated shows that the vertical carousel storage unit is a decoupled redundant project.

The use of system constraints linking some of the design parameters, allowed compacting the design equation, as to equal the number of DPs with the number of FRs. This operation, which result can be seen in Eq. (8), also reflects the rearrangement of the order of the DPs and stresses the decoupled condition of the design solution.

The system constraints allowed finding a mathematical model, which details are not in the scope of this paper, in order to define the main characteristics of the machine.

The paper shows that it is relatively easy to use the Axiomatic Design framework to help in the design of complex machines, taking into account the existing geometric and kinematic system constraints.

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References

[1] Suh NP. Axiomatic Design: Advances and Applications. New York: Oxford University Press, 2001. 528 p.
[2] Gonçalves-Coelho AM, Neştian G, Cavique M, Mourão A. Some Peculiarities of Redundant Design Solutions. Advanced Materials Research. 2014, 837: 49-54.
[3] Suh, NP. Complexity – Theory and Applications. New York: Oxford University Press, 2005. 312 p.
[4] Gonçalves-Coelho AM, Neştian G, Cavique M, Mourão A. Tackling with Redundant Design Solutions Through Axiomatic Design. International Journal of Precision Engineering and Manufacturing. 2012, 13 (10): 1837-1843.
[5] VRC Warehouse Technologies [Internet].; [cited 26th March 2016]. Available from: http://pt.vrc.pt/s/123.
[6] VRC Warehouse Technologies [Internet].; [cited 26th March 2016]. Available from: http://pt.vrc.pt/s/104.
[7] VRC Warehouse Technologies [Internet].; [cited 26th March 2016]. Available from: http://pt.vrc.pt/s/154.
[8] Rolla J. Modelação para Apoio ao Projeto de Armazéns Verticais Rotativos [master’s thesis]. FCT - Universidade Nova de Lisboa; 2015. 84 p. Portuguese.